PROGRESS ON A CAVITY WITH BERYLLIUM WALLS FOR MUON IONIZATION COOLING CHANNEL R&D*

D.L. Bowring†, A.J. DeMello, A.R. Lambert, D. Li, S. Virostek,
M. Zisman, LBNL, Berkeley, CA 94720, USA
D. Kaplan, IIT, Chicago, IL, 60616, USA
R.B. Palmer, BNL, Upton, NY 11973, USA

Abstract

The Muon Accelerator Program (MAP) collaboration is working to develop an ionization cooling channel for muon beams. An ionization cooling channel requires the operation of high-gradient, normal-conducting RF cavities in multi-Tesla solenoidal magnetic fields. However, experiments conducted at Fermilab's MuCool Test Area (MTA) show that increasing the solenoidal field strength reduces the maximum achievable cavity gradient. This gradient limit is characterized by an RF breakdown process that has caused significant damage to copper cavity interiors. The damage may be caused by field-emitted electrons, focused by the solenoidal magnetic field onto small areas of the inner cavity surface. Local heating may then induce material fatigue and surface damage. Fabricating a cavity with beryllium walls would mitigate this damage due to beryllium's low density, low thermal expansion, and high electrical and thermal conductivity. We address the design and fabrication of a pillbox RF cavity with beryllium walls, in order to evaluate the performance of high-gradient cavities in strong magnetic fields.

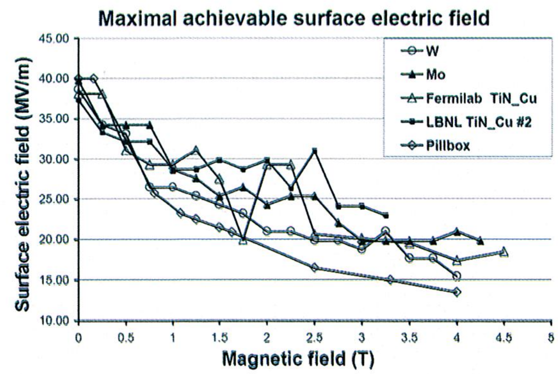

Figure 1: The maximum achievable surface electric field in an 805 MHz pillbox cavity, as a function of solenoial magnetic field strength. This plot shows similar behavior for various different materials: the maximum achievable gradient falls as magnetic field strength is increased [5].

INTRODUCTION

Cooling a muon beam must be done quickly, due to the muon's short lifetime. Ionization cooling is the preferred strategy for addressing this problem: the beam passes through an absorbing material which isotropically attenuates muon momentum, and then through an accelerating cavity which imparts only longitudinal momentum. This strategy requires high-gradient RF cavities to be placed in strong solenoidal focusing magnetic fields. RF and magnet parameters vary among proposed cooling designs [1]. As an example, the Muon Ionization Cooling Experiment (MICE) calls for 201.25 MHz cavities to operate at 16 MV/m in 2.5-3 T fields [2, 3, 4].

Normal-conducting RF cavities in solenoidal magnetic fields exhibit a reduction in the maximum safe operating gradient as the magnetic field strength increases, as shown in Figure 1 [5]. Specifically, the maximum achievable gradient is limited by the onset of RF breakdown which damages the cavity. Figure 2 shows the nature of this damage: $\sim$ 1 mm-diameter spots distributed over a wide area.

The physics of RF breakdown in strong magnetic fields is not well understood. Consequently, an extensive R&D

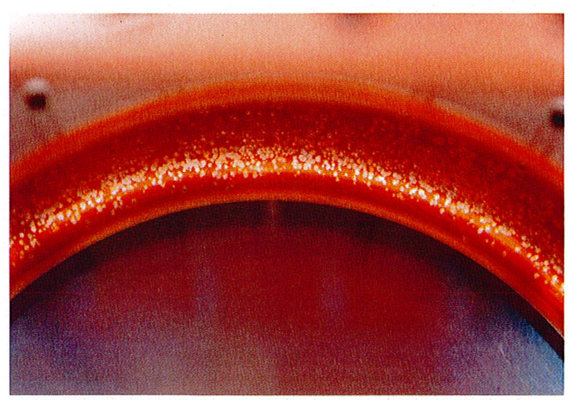

Figure 2: Breakdown damage on the iris of an 805 MHz pillbox cavity, after high-power testing in a magnetic field ramped from 0 to 3 T. $\sim$1 mm-diameter damage spots are distributed around the entire circumference of both cavity irises, as well as the end walls and opposite the input coupler (not shown). Photo credit: Fermilab Visual Media Services.

* Work supported by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

† dbowring@lbl.gov

effort is in progress to develop methods of suppressing or circumventing the problem. Various 805 MHz cavities have been built and tested at the MTA in pursuit of this goal. For example, a pressurized, hydrogen-filled cavity has been built to study the suppression of RF breakdown via the Paschen effect [6].

We present the design of a cavity intended to study and – ideally – circumvent the problem of RF breakdown in strong magnetic fields. The cavity is a simple pillbox with demountable beryllium end walls. The cavity operates at 805 MHz in the TM_{010} mode.

CAVITY DESIGN GOALS

The cavity design is driven by several basic questions pertaining to RF breakdown in high magnetic fields, as well as some MTA-specific considerations. This section discusses these design drivers.

201 MHz cavities for the MICE experiment and other cooling channel designs have 42 cm diameter irises in order to accommodate an uncooled muon beam with large transverse emittance. These irises are closed by 0.38 mm-thick beryllium windows (effectively transparent for muon beams) in order to increase the cavity's shunt impedance. An 805 MHz pillbox cavity with Be windows ("LBNL-01") was fabricated previously, to serve both as a 1/4-scale model of the 201 MHz cavity and as a prototype cavity for cooling further downstream [7]. RF breakdown in strong magnetic fields was observed in this cavity, as shown in Figure 1. It was observed that while the interior Cu surfaces of the pillbox cavity were damaged during breakdown (as in Figure 2), the Be windows remained undamaged.

Pulsed heating damage from focused, field-emitted electrons may cause surface damage and instigate breakdown [8]. Fabricating a cavity with beryllium end walls may prevent breakdown damage, permitting more stable cavity operation at high gradients. It is likely that beryllium's comparatively low density, high melting temperature, and long radiation length protect it from arc damage.

We expect damage to cause more damage. Breakdown results in pitting, cracking, and other surface deformations. Irregular surface features may have field enhancement factors sufficient to generate large Fowler-Nordheim current densities, seeding further breakdown events. Surface damage has historically been addressed by refurbishing the cavity via mechanical polishing, with mixed results. An easier and more thorough approach would be to replace cavity components as they become damaged. This can be accomplished by adopting a simple pillbox design with demountable end walls. The cavity is then modular: damaged components may be quickly and (comparatively) cheaply replaced. Furthermore, it becomes straightforward to evaluate breakdown performance for different materials. For example, pulsed heating effects may be mitigated by fabricating end walls out of alloys such as CuZr or Glidcop [9]. A modular approach also permits variation of the cavity length, which in turn would allow the study of (a) the effect of RF phase on the field-emitted electron impact energy, and (b) the effect of stored energy on the behavior of breakdown plasmas [10].

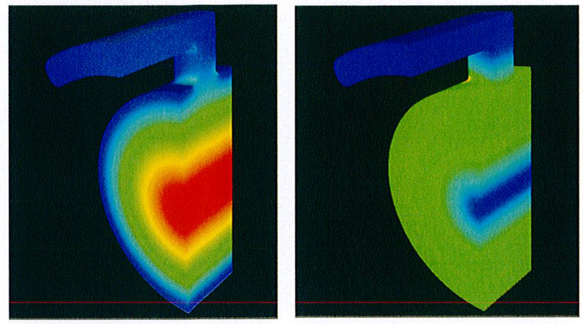

Figure 3: Electric (left) and magnetic (right) fields in a cut view of the modular, beryllium wall cavity. Simulated using ACE3P [11].

Finally, the magnetic field in the MTA is provided by a superconducting solenoid with a 22 cm warm-bore radius. An ideal 805 MHz pillbox cavity operating in the TM_{010} mode has a 14.3 cm inner radius. There has been some design effort spent on fitting the cavity inside the magnet, along with other elements like coupling waveguides, flanges, coolant pipes, instrumentation, etc. This problem is addressed for LBNL-01 by introducing RF power through a kidney-shaped hole in the end wall, resulting in large, off-axis surface electric fields. This, in turn, creates uncertainty about the nature and origin of breakdown events. We require a cavity with a more standard coupling scheme, in which power is coupled into the cavity at its equator. Fitting such a coupling scheme into the warm-bore magnet radius requires the use of a curved transition waveguide piece, as shown in Figures 3 and 4.

RF AND MECHANICAL DESIGN

RF simulations of the modular, beryllium-wall cavity were performed using ACE3P[1], developed at SLAC [11]. Electric and magnetic fields in a cross section of the cavity are shown in Figure 3. Power is coupled into the cavity using a curved waveguide, as discussed above. The TM_{010} mode resonates at 804.99 MHz. The design is slightly overcoupled ($\beta = 1.3$) to account for material imperfections, manufacturing tolerances, and other real-world sources of loss. Finally, the on-axis surface electric field is ~ 4 times larger than the off-axis peak electric field. As discussed in the previous section, this helps to constrain RF breakdown events to the beam axis. Interior corners are rounded in relevant places, in order to suppress multipacting. The RF cavity parameters are summarized in Table 1.

The cavity is composed of four main sections, as shown in Figure 4: two demountable end walls, a central copper ring and coupling/transition waveguide, and a standard WR975 waveguide leading to the klystron. A spring seal

[1]Computing time with ACE3P provided by US DOE at NERSC.

Table 1: RF Parameters, simulated using ACE3P

Frequency (MHz)	804.99
Radius (mm)	142.07
Length (mm)	104.4
Q_0	20472
R/Q (Ω)	220
β	1.3

and a viton O-ring make the RF and vacuum seals, respectively, between the demountable end walls and the central copper ring. The demountable end walls are fastened to the cavity using nonmagnetic stainless steel bolts, as well as a stainless steel retaining ring that uniformly distributes pressure around the beryllium wall. The coupling waveguide is joined to the cavity body by an electron beam weld. Finally, the transition waveguide is mounted to the WR975 by a similar assembly of spring seal, O-ring, and stainless steel bolts. Note the "thin spots" milled into the beryllium walls on axis. These capitalize on the low density of beryllium to facilitate dark current measurements and other diagnostics. Nominal Be wall thickness is 6.35 mm, pending finite element strain analysis.

CURRENT AND FUTURE WORK

Beryllium particulate presents a respiratory hazard. There is then some concern about excess strain on Be components from cavity vacuum pressure and differential RF heating. Finite element strain simulations are underway to gauge the safety and structural stability of the solid Be components. Fabricaton drawings are being prepared for a final design review in the very near future.

ACKNOWLEDGEMENTS

Thanks to Alan Bross, Chris Adolphsen, Zenghai Li, Tianhuan Luo, Al Moretti, Mark Palmer, and Yagmur Torun for their helpful advice in pursuit of this cavity design.

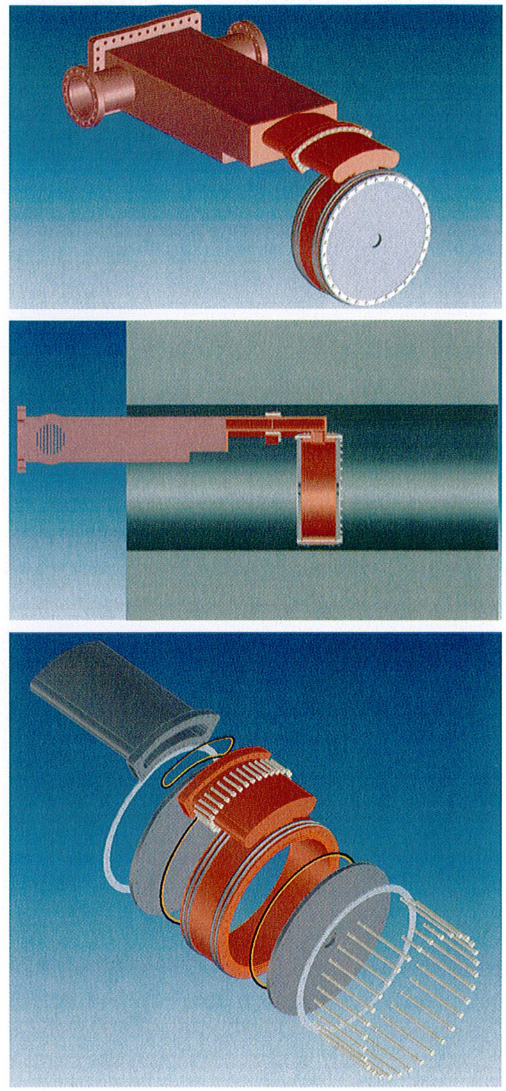

Figure 4: Perspective (top), cut view with magnet (middle), and exploded (bottom) views of the modular, beryllium wall cavity.

REFERENCES

[1] R.B. Palmer et al., "A complete scheme of ionization cooling for a muon collider," PAC'07, Albuquerque, June 2007, THPMS090, p. 3193 (2007), http://www.JACoW.org

[2] M.A. Green and J.M. Rey, IEEE Trans. Appl. Supercon. 13 (2003) 2.

[3] M.S. Zisman, "Status of the international muon ionization cooling experiment (MICE)," PAC'07, Albuquerque, June 2007, THPMN119, p. 2996 (2007), http://www.JACoW.org

[4] T. Luo et al., "Progress on the MICE 201 MHz RF cavity at LBNL," THPPC049, these proceedings.

[5] D. Huang et al., "RF studies at Fermilab MuCool Test Area," PAC'09, Vancouver, May 2009, TU5PFP032, p. 888 (2009), http://www.JACoW.org

[6] K. Yonehara et al., "Investigation of breakdown plasma in high-pressure hydrogen gas filled RF cavity," MOPPC036, these proceedings.

[7] D. Li et al., "Design and fabrication of an 805 MHz RF cavity with Be windows for a high RF power testing for a muon cooling experiment," PAC'01, Chicago, June 2001, 918, http://www.JACoW.org

[8] D. Stratakis, J.C. Gallardo, and R.B. Palmer, Nucl. Inst. Meth. A 620 (2010), 147-154.

[9] L. Laurent et al., PRST-AB 14 (2011) 1-21.

[10] J. Norem et al., "Progress in modeling arcs," THEPPB013, these proceedings.

[11] K. Ko et al., "Advances in parallel electromagnetic codes for accelerator science and development," LINAC2010, Tsukuba, Japan.